CONVERTER WITH INDUCTOR AND DIGITAL CONTROLLED TIMING

BACKGROUND OF THE INVENTION

(1)   Field of the Invention

The present invention relates to the general subject of electronic power supply converters for energy wherein one example is a boost converter system having a power factor correction (PFC) that is running in discontinuous mode using an equation to calculate the point of time the zero-current state of the storage inductor occurs without the requirement of a secondary winding or special voltage comparators to detect zero current to achieve maximum power transfer and to avoid a continuous mode operation.

(2) Description of the Prior Art

The design of a boost converter system with a power factor converter (PFC) requires small storage inductors together with high transferred power. These two parameters are counteracting against each other. The transferred power reaches its maximum if the storage inductor is recharged right after the inductor reaches the zero current state.

Prior art power supplies are using either secondary windings, special voltage comparators or analog current sensing circuits to detect the zero-current state of the storage inductor.

US Patent 5,757,166 to Sodhi teaches a power correction factor boost converter. A secondary winding is used for zero current detection of the storage inductor.

US Patent 5,861,734 to Fasullo et al describes a control system for a boost converter using 2 interleaved boost circuits. A current sensing circuit is provided that senses the current in each of the boost converters. 2 boost converter switches have to be controlled.

US Patent 6,178,104 B1 to Nak-Choon-Choi describes a power factor correction circuit using reverse saw tooth waves. The switch is coupled to a resistor and a capacity that by forming a current detector, detect the current flowing through the storage inductor of the boost converter. The PFC circuit is using reverse saw tooth waves and is controlling the slope of the current.

Fine adjustment of the energy transfer overcoming the limitations of discrete time in digital systems is a known problem. U.S. Patent 6,043,633 to Lev et al. discloses a method and an apparatus for controlling a boost converter that offers power factor correction by compensating for the parasitic capacitance and parasitic oscillations. A zero current detector

facilitates the compensation. A dithering method to enhance the time resolution of clocked digital circuits is presented.

SUMMARY OF THE INVENTION

A principal object of the present invention is to provide a highly effective electronic power supply converter such as a boost converter having maximum power, related to the size the of the storage inductor, transferred without the requirement of a secondary winding or voltage comparators.

A further object of the present invention is to provide a highly effective boost converter with a power factor corrector (PFC) having maximum power, related to the size the of the storage inductor, transferred without the requirement of a secondary winding or voltage comparators.

A further object of the present invention is to recharge the storage inductor right after the point of time when zero current state occurs at the storage inductor. This is key to a maximal transfer of energy.

A still further object of the present invention is to achieve a fine adjustment of the energy transfer to minimise distortion and harmonics overcoming the limitations of discrete time steps in clocked digital systems.

Another still further object of the present invention is to achieve an optimal accuracy of the measurement of the voltages at the source and the load side to achieve best accuracy to define the point of time of the zero current state of

the storage inductor and furthermore to achieve best accuracy required as input for the fine-tuning of the energy transferred.

Another still further object of the present invention is to achieve less manufacturing costs and to reduce the number of components required by avoiding secondary windings or voltage comparators for the zero current detection.

In accordance with the objects of this invention a system used for converting electronic power supply energy has been achieved. This system can be used as a boost converter or a DC to DC converter. Maximal power is transferred by recharging the storage inductor right after the point of time when zero current occurs at the storage inductor, As an example of the usage of the invention a boost converter with PFC (power-factor-corrector) having maximal power transferred related to the size of the storage inductor by recharging the storage inductor right after the point of time when zero current state occurs at the storage inductor is achieved. Fig. 1 illustrates the main components of the system. The boost converter is including a storage inductor coupled to an input voltage, a shunt switch controlling a current flowing through said storage inductor and a rectifying diode for rectifying the output voltage. Furthermore the system comprises of an analogue/digital converter which is converting analogue values measured and reference voltages into digital values required by a digital control unit to control frequency and pulse width of the shunt switch using means to calculate the point of time when zero current state occurs instead of detecting this point of time using secondary

windings or other analog circuits. Said digital control unit initiates the recharging of the storage inductor right after the point of time of the zero current state is reached.

In accordance with an object of the invention a method of calculating the point of time of the zero current state of the storage inductor is achieved. Said point of time is calculated using an equation based on the ON time of said shunt switch and the voltages measured at the source side (rectified mains supply) and the load side. A safety margin to balance inaccuracies of the measurement is added to this calculated point of time.

In accordance with another object of the invention to minimize distortion and harmonics a fine adjustment of the energy transfer through fine tuning of the pulse width of the shunt switch is introduced overcoming the limitations of discrete time steps in clocked digital systems. This is achieved by either using patterns or by a digital delta sigma modulator that is averaging the ON time values of the shunt switch by toggling between neighboring ON time values (pulse-width) and controlled by said digital control unit.

In accordance to the object of this invention the calculation of the point of time of the zero current state of the storage inductor and the fine-tuning of the energy transferred require a very high accuracy of the measurement of the voltages at the load side, the inductor side and at the source side. This is achieved by a calibration of the tolerances of the voltage dividers used for these measurements. The voltage divider ratios can be measured at

appropriate periods of time (see Fig. 7) considering the small influence of the

voltage of the forward bias of the diode in the magnitude of 0.7volt hence.

This calibration enables the usage of tolerant voltage dividers. Said digital

control unit is controlling the calibration of said voltage dividers.

In accordance with the objects of the invention said three methods of (1)

calculating the point of time of the zero state of the storage inductor and (2) of

fine-tuning the energy transfer and (3) of calibrating the voltage dividers to

improve the accuracy of the voltages measured can all be used separately or

used in any combinations together.

BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings forming a material part of this description, there is shown:

Fig.**1** illustrates the preferred principal embodiment of the PFC (Power-Factor-Corrector) boost converter consisting of one storage inductor, a rectifier diode, a shunt switch, voltage dividers and a control unit containing an analog-to-digital converter, a delta-sigma modulator and a logical unit.

Fig.**2A** illustrates the principal currents of the power supply.

Fig. **2B** illustrates the waveforms of the currents of Fig. **2A** as functions of the switch **S**.

Fig. **3** illustrates the flow of the current **IL** through the storage inductor dependent of the ON time of the switch and the transfer time **TTR** of the energy.

Fig. **4** illustrates the principal wave form of the current through the storage inductor **IL** related to the ON time of the switch and the period and the amount of energy transfer **Euc** related to the ON time.

Fig. **5** illustrates one method how the point of time of zero current is calculated.

Fig. **6** illustrates one method how to do the fine adjustment of the energy transferred.

Fig. **7** illustrates one method how to improve the accuracy of voltage measurement by calibrating the voltage dividers.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The preferred embodiments disclose a novel system used as converters for energy in electronic power supply systems. Said system, running in discontinuous mode, can be used in simple boost converters or in boost converters having a PFC (power-factor-correction) or can be used as an DC-to-DC converter that is running in a discontinuous mode. Some parts of the invention are applicable to other power electronic systems as well. The design of such converters requires small inductors together with maximal power transferred. These two parameters are counteracting against each other. The power transferred reaches its maximum when the storage inductor is recharged immediately after reaching the zero current state. For the detection of the zero current generally a secondary winding at the storage inductor is used. As an example of the invention a configuration of the principal components of a boost converter with PFC is shown in Fig. 1. The main components are the storage inductor L, the rectified main supply U1, the shunt switch S, the rectifier diode D, the voltage dividers pairs Z11 - Z12, Z21 - Z22 and Z41 - Z42 are used for the measurement of the voltages of the mains supply U1, the voltage of the inductor output US, the voltage at the load side UC, the reference voltage Uref and a oscillator driven digital control unit to control the frequency and pulse width of the shunt switch S.

Fig. **2A** shows the principal layout of a boost converter and Fig. **2B** shows the flow of the currents flowing through the storage inductor **L**, the shunt switch **S** and the rectifying diode **D**. Said boost converter is operating in a discontinuous mode. The current **IS** starts to flow after the switch **S** is closed (or ON), the current **IL** is rising as long the switch **S** is ON (short pulse width) and is decreasing during the time period **TTR.** The time period **TD** describes the time period when no current is flowing. In a discontinuous mode this time period must be equal or greater than zero. The current **ID** at the load side starts to flow when the switch **S** is opened (or in OFF state) and is decreasing during the period of energy transfer **TTR.**

This invention proposes to calculate the point of time when the current through the storage inductor **IL** reaches the zero state. This happens always after the switch S is opened with the delay **TTR. TTR** is the period of energy transfer. **TTR** can be calculated using the ON time **Ton** of the switch and the voltages **U1** and **UC.** The voltage across the storage inductor is

$$UL = L * \frac{dI}{dt}$$

The maximum current through the storage inductor (see Fig. **3** and Fig.**2 A+B)** is

$$ILMAX = \frac{U_1 - U_S}{L} * TON$$

During the time period the switch is closed the voltage **Us** equals zero. This means

$$ILMAX = \frac{U_1}{L} * TON$$

The transfer time TTR of the current ID is therefore

$$\text{TTR}=\frac{I_{LMAX}*L}{U_S-U_1}=\frac{U_1*T_{ON}}{U_S-U_1}.$$

The forward voltage of the diode **D** is in the range of 0.7 Volts. In the

forward mode

Us=Uc+0.7 volts

The final equation to calculate the transfer time is

$$\text{TTR}=\frac{U_1*T_{on}}{Uc+0.7V-U_1}$$

Using this equation the point of time To of the zero current state of the

current IL can be calculated.

A method how to calculate said To is illustrated in Fig. **5**. When the total

system is inactive

U1 = Us = Uc + 0.7 volts.

In step **51** the system starts with a low value of **Ton** to avoid saturation of

L. In step **52** the input voltage U1 is measured. In step **53** the shunt switch is

closed for time **Ton**. In step **54** the switch **S** is opened after the pulse width

Ton. In the next step **55** the voltages **U1** at the source side and **Uc** at the load

side are measured immediately after the switch is opened. Usually the

switching frequency of the converter is much higher than the mains frequency

or the variation of the voltage **Uc**. If switching intervals are short related to the

frequency of the mains supply, which is the case under normal conditions of

operations, these measurements can be performed any time but preferably in

step **52** already when the input voltage U1 is measured and step **55** can be

skipped. The noise level of U1 and Uc is much lower than at Us. In step **56** the digital control is calculating the transfer time period TTR according to the equation above. In step **57** TTR is added to the falling edge of the **Ton** pulse to get the point of time To of the zero current state of the current IL. In step **58** a safety margin of e.g. 1 clock cycle or 100ns is added before the next cycle starts with step **52** again. This safety margin is required to avoid the risk that the converter goes into a continuous mode with great power dissipation. Above-mentioned method is used to define the frequency of the boost converter system.

The amount of energy transferred is mainly a function of the pulse width **Ton**. Fig. **4** illustrates how the pulse width **Ton** correlates to the energy transferred **EUC**. Power converters, that make low distortion and harmonics, need a fine adjustment of the ON time of the switch. But in digital systems the ON-time is discrete. In order to overcome the discreteness of the time steps an averaging of neighbouring discrete ON time values (pulse width) is introduced.

The method used for the fine adjustment of energy is illustrated in Fig. **6**. In step **61** the voltage at the load side Uc is monitored through the voltage divider **Z41** and **Z42** and by the **A/D converter** of Fig.1. In step **62** the digital control unit compares Uc with the reference voltage **Uref** (see Fig.1) digitised as well by said **A/D converter**. In step **63+64** the digital control unit is adjusting the pulse-width **Ton** according to the comparison result of Uc and **Uref** and is increasing or reducing the pulse-width **Ton** accordingly to reach

equivalence between **Uc** and **Uref** in order to adjust the energy transferred. In the step **63** the gross adjustment is done. In case of small differences between **Uc** and **Uref** step **64** illustrates the averaging of neighboring **Ton** values to fine-tune the energy transferred. The averaging is done by either using defined patterns to vary the on time of the switch ("toggling") in minimal steps possible or by using digital delta-sigma modulation with a multilevel quantifier. One digital quantifier level corresponds to the period to load the storage inductor. The delta-sigma principle as an averaging principle makes the use of digital systems with moderate clock frequency possible. This fine adjustment of the ON time using a digital delta sigma modulator is very useful for a SEPIC (single ended primary inductor converter) when the load variation is large and the ON times of the switch are short. For the time period a SEOIC is inactive, **Uc** = 0. Increasing switching frequency and increasing **Ton** increases **Uc** in all systems used.

For the said calculation of the point of time of the zero current state in the storage inductor and for the control of the pulse-width **Ton** by said comparison of **Uc** and **Uref** an accurate measurement of the voltage at the source side **U1**, the voltage on the storage inductor **Us** and the voltage at the load side **Uc** is necessary (see Fig.1). This invention proposes to increase the accuracy of the measurement with a calibration of the voltage dividers $\frac{Z11}{Z12}, \frac{Z21}{Z22}$ and $\frac{Z31}{Z32}$ (see Fig. 1) to overcome the tolerances of the voltage dividers. This enables the usage of tolerant voltage dividers without losing accuracy of the measurement.

Fig. **7** illustrates the method how and during which time periods the calibration can be performed. Step **71+72** explain the period of zero current state of the storage inductor is used to measure the ratios of the voltage dividers $\dfrac{Z11}{Z11+Z12}$ and $\dfrac{Z21}{Z21+Z22}$. Step **73+74** explain that during the energy transfer period **TTR** the diode **D** is forward biased. The voltage across the diode **D** is well known, it is about 0.7 Volts and much lower than the voltage to be measured. During the forward bias of the diode **D** the voltage at the storage inductor **Us** equals the voltage at the load side **Uc** plus 0.7Volts. Hence the voltage divider ratios $\dfrac{Z32}{Z32+Z31}$ and $\dfrac{Z22}{Z21+Z22}$ can be measured. The digital control unit uses the measured values of the voltage divider ratios to calculate more precisely the point of time of the zero current state and to control more precisely the pulse width **Ton**.

The methods of (**1**) calculating the point of time of the zero current state of the storage inductor (Fig. **5**) and of (**2**) of fine-adjusting of the energy transferred (Fig. **6**) and of (**3**) improving the accuracy of voltage measurements by calibrating the voltage dividers (Fig. **7**) can be used either individually or together in any combination. The highest efficiency of this kind of power supply combined with minimal distortion and harmonics will be achieved by a combination all three said methods together. For more simple requirements a solution could be achieved with just one or two of said methods.

While the invention has been particularly shown and described with reference to the preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made without departing from the spirit and scope of the invention.

What is claimed is: